APPLICATION OF PROTECTIVE RELAYS IN A POWER SYSTEM

by

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INTRODUCTION

Protective relaying is one of several features of system design concerned with minimizing damage to equipment and interruption to service when electrical failures occur.

The function of protective relaying is to cause the prompt removal from service of any element of a power system when any abnormal operation occurs which might cause damage or otherwise interfere with the effective operation of the rest of the system. A secondary function is to provide indication of the location and type of failure. There are two groups of relaying equipment; "Primary" relaying and "back-up" relaying. Primary relaying is the first line of defense, whereas "back-up" relaying functions only when primary relaying fails.

The contribution of protective relaying is to help the rest of the power system to function as efficiently and as effectively as possible in the face of trouble. The ability of protective relaying to permit fuller use of the system capacity is illustrated by system stability. More load can be delivered over an existing system by speeding up the protective relaying (see Fig. 1).

RELAY OPERATING PRINCIPLES AND CHARACTERISTICS

For every type and location of failure, there is some distinctive difference; magnitude, frequency, phase angle, duration, rate of change, direction or order of change, harmonic or wave shape in voltage or current, and there are various type of protective relaying equipment available, each of which is designed to recognize a particular difference and to operate in response

to it.

There are only two fundamentally different operating principles: 1) Electromagnetic attraction, and 2) Electromagnetic induction.

Electromagnetic Attraction. For single quantity relays, if the effect of saturation is neglected, the total actuating force may be expressed as

$$F = K_1 I^2 - K_2$$

where F = net force

K_1 = a force conversion constant

I = the rms magnitude of current in actuating coil

K_2 = the restraining force, including friction.

When the relay is on the verge of picking up, the net force is zero, and the operating characteristic is

$$I = \sqrt{\frac{K_1}{K_2}} = \text{constant}$$

For directional relays, the force tending to move an armature may be expressed as $F = K_i I_p I_a - K_2$

where F = net force

K_1 = a force conversion constant

I_p = the magnitude of current in the polarizing coil

I_a = the magnitude of current in the armature coil

K_2 = the restraining force, including friction and the operating characteristic is

$$I_p I_a = \frac{K_2}{K_1} = \text{constant}$$

I_p and I_a are assumed to flow through the coils in such directions that a pick up force is produced.

It is evident that if the direction of either I_p or I_a is reversed, the direction of force will be reversed as shown in Fig. 2.

Electromagnetic Induction. Actuating force is developed in a movable element, that may be a disc or other form of rotor of non-magnetic current conducting material, by interaction of electromagnetic fluxes with eddy currents that are induced in the rotor by these fluxes as shown in Fig. 3.

The fluxes may be expressed as follows:

$$\phi_1 = \Phi_1 \sin \omega t$$

$$\phi_2 = \Phi_2 \sin(\omega t + \theta)$$

where θ is the phase angle by which ϕ_2 leads ϕ_1

If self-inductance is neglected

$$i_{\phi_1} \propto \frac{d\phi_1}{dt} \propto \Phi_1 \cos \omega t$$

$$i_{\phi_2} \propto \frac{d\phi_2}{dt} \propto \Phi_2 \cos(\omega t + \theta)$$

Total force $= (F_2 - F_1) \propto \phi_2 i_{\phi_1} - \phi_1 i_{\phi_2}$

Total force $\propto \Phi_1 \Phi_2 [\sin(\omega t + \theta) \cos \omega t - \sin \omega t \cos(\omega t + \theta)]$

Total force $\propto \Phi_1 \Phi_2 \sin \theta$

The direction of the force, and hence the direction of motion of the movable member of the relay depends upon which flux is leading the other, and the maximum force is produced when the two fluxes are 90° apart.

Single Quantity Induction Relays. The torque may be expressed as $T = K_1 I^2 - K_2$ when I is the rms magnitude of total current. The phase angle between the individual currents is a design constant.

Direction Induction Relays. The expression for torque becomes:

$$T = K_1 I_1 I_2 \sin \theta - K_2$$

I_1 and I_2 : the rms value of actuating currents

θ : phase angle between the rotor piercing flux produce by I_1 and I_2

For "symmetrical" structures θ may be defined as the angle between I_1 and I_2.

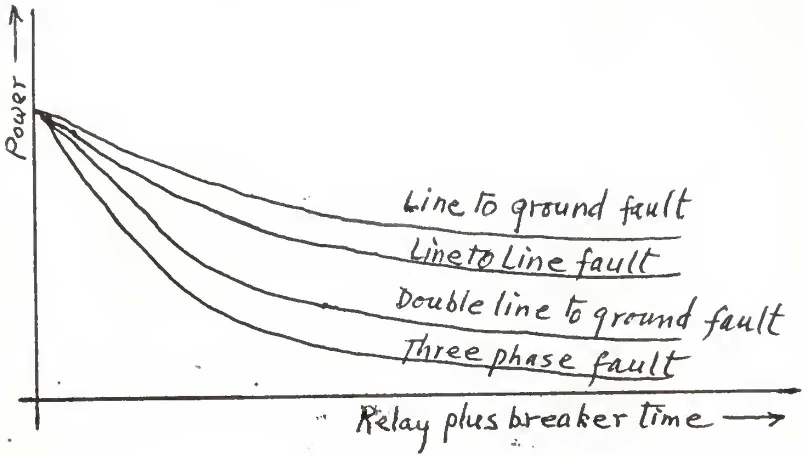

Figure 1. Curve illustrating the relation between relay-plus-breaker time and the maximum amount of power that can be transmitted over one particular system with out loss of synchronism when various faults occur.

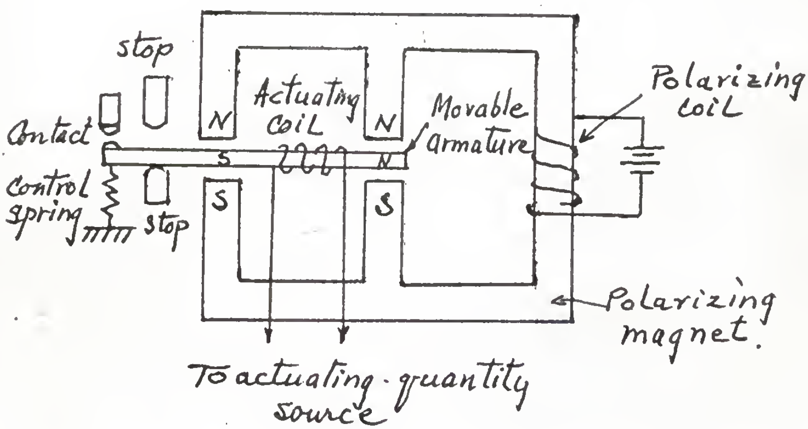

Figure 2. Directional relay of the electromagnetic attraction type.

As shown in Fig. 4, if τ is used as the "angle of max. torque", the torque expression may be written in such a way that it will apply to all relays whether "symmetrical" or not as follows:

$$T = K_1 I_1 I_2 \cos(\theta - \tau) - K_2$$

The Operating Characteristic of a Directional Relay. For a current-voltage directional relay

$$VI \cos(\theta - \tau) = \frac{K_2}{K_1} = \text{constant}$$

The polarizing quantity V is the reference and its magnitude is assumed to be constant; therefore,

$$I \cos(\theta - \tau) = \text{constant}$$

Any I phasor whose head lies in the positive torque areas will cause pick up. For a different magnitude of reference V the operating characteristic will be another straight line parallel to the one shown and related to it by the expression $VI_{min.} = $ constant. This operating characteristic can be shown on a polar-coordinate diagram, as in Fig. 5.

Differential Relays. The definition of such a relay is "one that operates when the phasor difference of two or more similar electrical quantities exceeds a predetermined amount". See Fig. 6.

Impedance-Type Distance Relays. In an impedance relay, the torque produced by a current element is balanced against the torque produced by a voltage element. The current element produces positive (pick up) torque. See Fig. 7.

$$T = K_1 I^2 - K_2 V^2 - K_3 \qquad K_3 : \text{spring effect}$$

At balance

$$\frac{V}{I} = Z = \sqrt{\frac{K_1}{K_2} - \frac{K_3}{K_2 I^2}}$$

$$Z \quad \sqrt{\frac{K_1}{K_2}} = \text{constant}$$

since $\frac{K_3}{K_2 I^2} \approx 0$

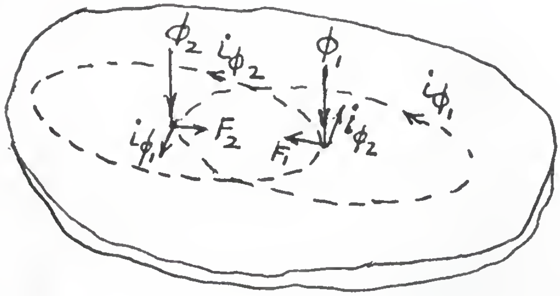

Figure 3. Torque production in an induction relay

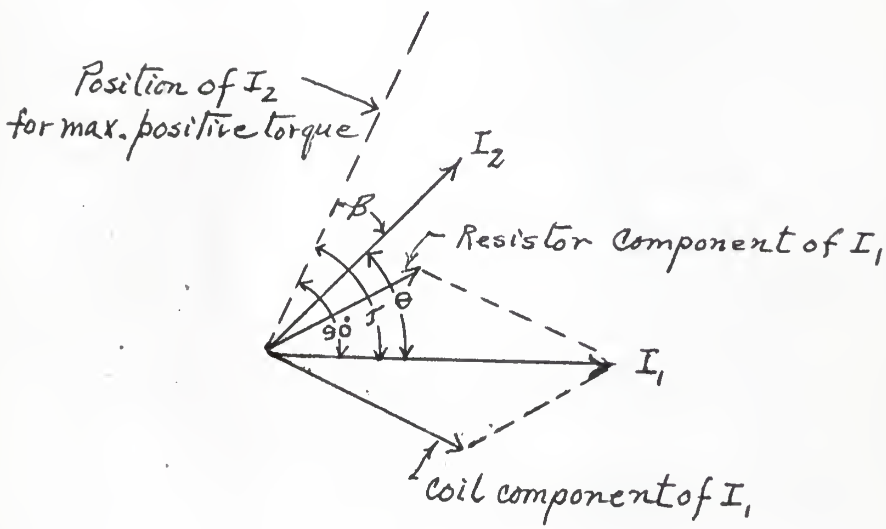

Figure 4. Phasor diagram for maximum torque in a current-current induction type directional relay.

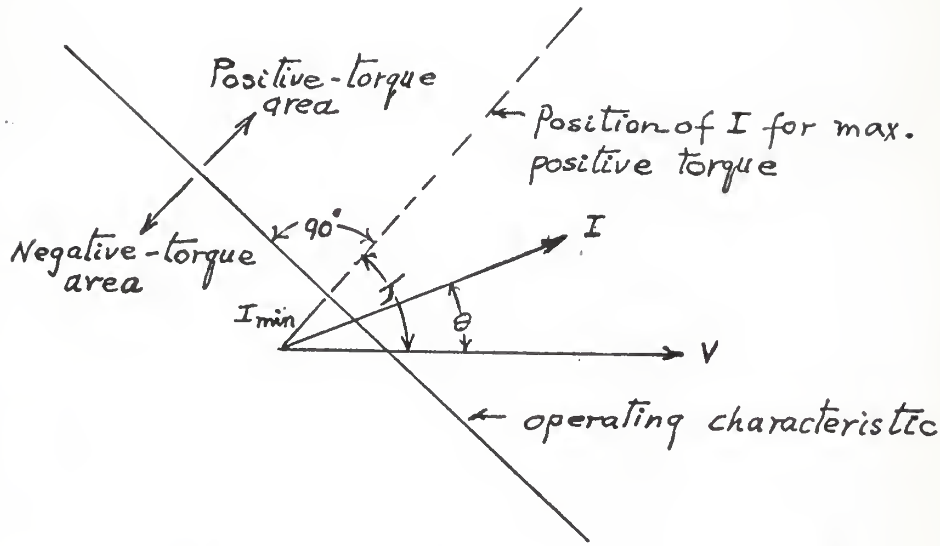

Figure 5. Operating characteristic of a directional relay on a polar co-ordinates.

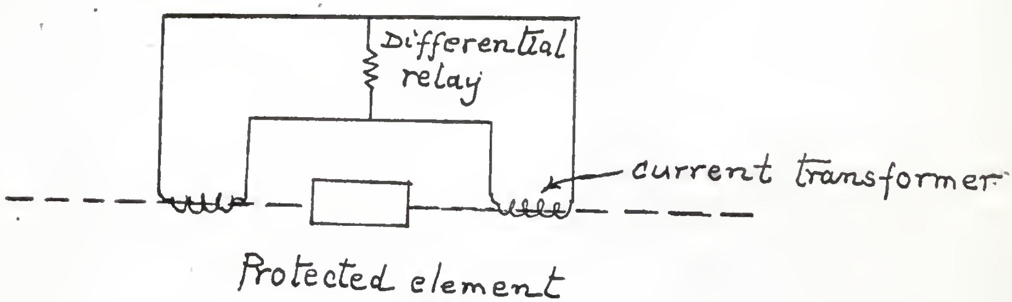

Figure 6. A simple differential-relay application.

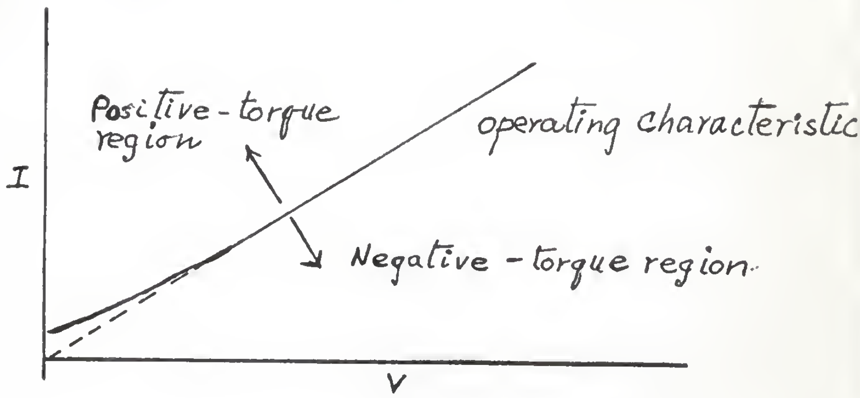

Figure 7. Operating characteristic of an impedance relay.

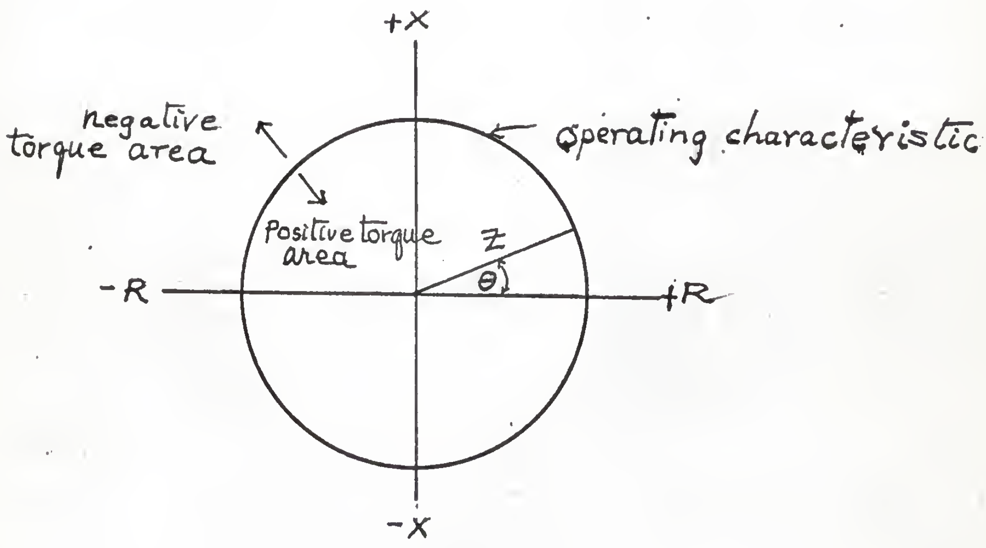

Figure 8. Operating characteristic of an impedance relay on R-X diagram.

The relay will pick up for any combination of V and I represented by a point above the operating characteristic in the positive torque region, or for any value of Z less than the constant value represented by the operating characteristic. See Fig. 8.

$$Z = \frac{V}{I} = \text{length of a radius vector}$$

$$\theta = \text{phase angle between V and I}$$

If I is in phase with V, the phasor lies along positive R.

If I lags V the phasor has a positive X component.

Fig. 9 shows the relation of the directional unit operating characteristic to the impedance unit characteristic on the same R-X diagram. Since the directional unit permits tripping only in its positive torque region, the inactive portion of the impedance-unit characteristic is shown dashed.

Pilot Relaying. Pilot relaying is an adaptation of the principle of differential relaying for protection of transmission line sections. This method involves current and voltage at both ends of the protected line section. The means of transmitting information from each end of the line to the other are wire circuits, called "pilot wires", operating at power-system frequency, or carrier current channels using the conductors of the protected line itself and operating at superposed radio frequency, or the microwave pilot. The operating principle is current comparison and phase comparison. If the magnitudes or phase angles at the two ends differ by more than a certain amount, the difference is evidence of existence of a fault in the protected section.

Directional Comparison And Transferred Tripping. A scheme in which a directional fault detector relay at each end shows the direction to the fault. If the fault is on the protected line the relay will trip the breaker at the near end of the line and send a signal to the distant end to trip the breaker there.

CONVENTIONS FOR SUPERIMPOSING RELAY AND SYSTEM CHARACTERISTICS

In order to superimpose the plot of a relay characteristic on the plot of a system characteristic to determine relay operation, both plots must be on the same basis.

Where the distance relay is shown to be energized by voltage and current at a given location in the system the co-ordinates of the impedance point on the R-X diagram representing a tripping direction of the relay will have signs as shown in table I. Leading reactive power is here considered to flow in a certain direction when current flows in that direction as though into a load whose reactance is predominantly capacitive, see Fig. 10.

TABLE I Conventional Signs Of R & X

Condition	Sign of R	Sign of X
Power from A toward B	+	
Power from B toward A	—	
Lagging reactive power from A toward B		+
Lagging reactive power from B toward A		—
Leading reactive power from A toward B		—
Leading reactive power from B toward A		+

The following relations give the numerical value of R and X for any balanced three phase condition.

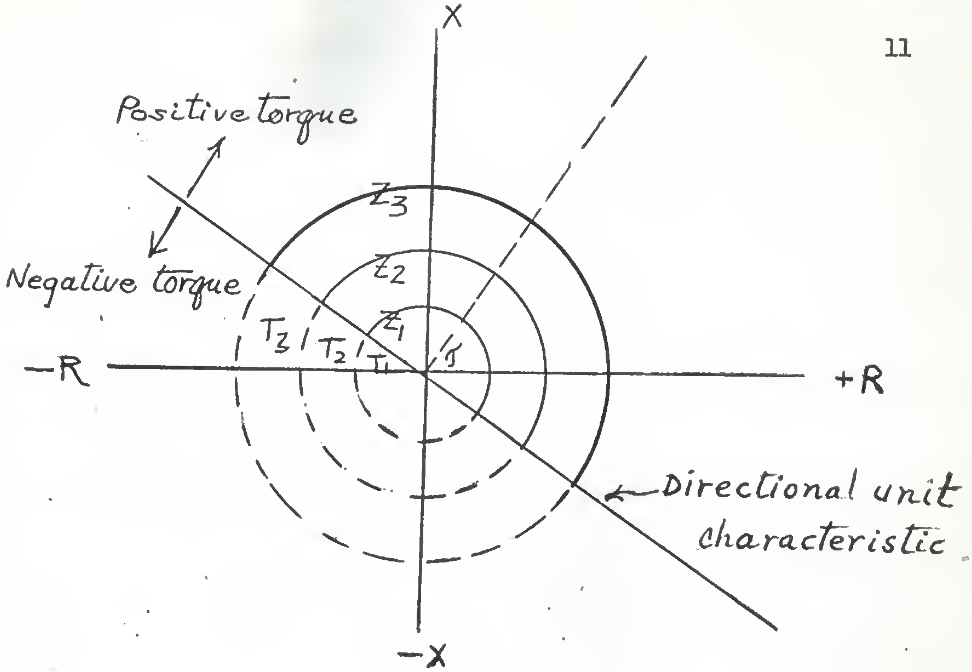

Figure 9. Operating and time-delay characteristic of an impedance type distance relay.

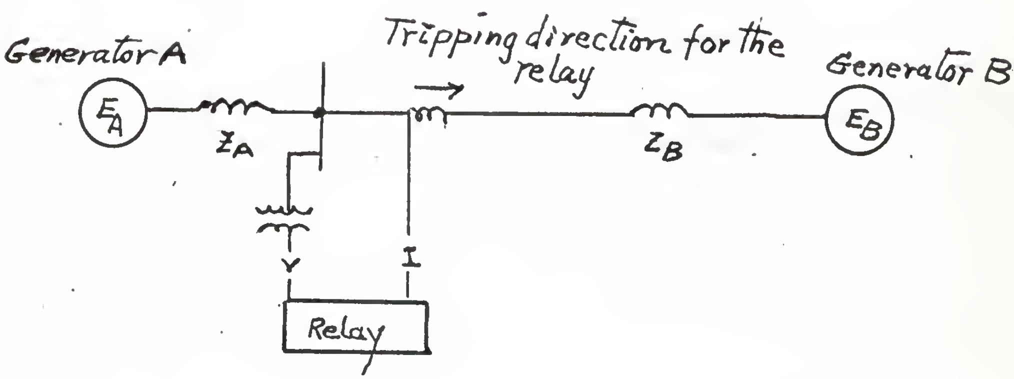

Figure 10. Illustration of the convention for relating relay and system characteristics on the R-X diagram.

$$R = \frac{V^2 W}{W^2 + (RVA)^2}$$

$$X = \frac{V^2 (RVA)}{W^2 + (RVA)^2}$$

where V is the phase to phase voltage.

W is the three phase power, and (RVA) is the three phase reactive power. R and X are components of the positive sequence impedance which could be obtained under balanced three phase conditions by dividing any phase to neutral voltage by corresponding phase current. All of the quantities in the formula must be expressed in actual values (ohms, volts, watts, and reactive volt-amperes), or all in per cent or per unit.

By applying the proper signs to R and X one can locate the point on the R-X diagram representing the impedance for any balanced three phase system condition. For example, the point P of Fig. 11 would represent a condition where power and lagging reactive power were being supplied from A toward B in the tripping direction of the relay.

For a relay in the system of Fig. 10 whose tripping direction is opposite to that shown interchange A and B in the designation of the generator of Fig. 10 and in table I; in other words, follow the rule already given that the signs of R and X are opposite when power and lagging reactive power flow in the tripping direction of the relay.

For example, if point P represents a given condition of power and reactive power flow as it appears to the relay then to a relay with opposite tripping direction the same condition appears as a point diametrically opposite to P.

Occasionally, it may be desired to show on the same diagram the characteristics of relays facing in opposite directions. Then the rule cannot be followed, and care must be taken to avoid confusion.

By referring to Fig. 10.

$$\frac{V}{I} = Z = \frac{E_A Z_B + E_B Z_A}{E_A - E_B}$$

where all quantities are complex numbers, and E_A and E_B are the generated voltage of generators A and B respectively. Therefore, in general, Z is not directly related to any actual impedance of the system. From this general equation, system characteristics can be developed for loss of synchronism between the generators or for loss of excitation in either generator.

For normal load loss of synchronism, loss of excitation, and three phase faults (all balanced three phase conditions), a system characteristic has the same appearance to each of the three distance relays that are energized from different phases. For unbalanced short circuits, the characteristic has a different appearance to each of the three relays, as will be shown later in this report.

By using distance type relay units individually or in combination, any region of the R-X diagram can be encompassed or set apart from another region by one or more relay characteristics. With the knowledge of the region in which any system characteristic will lie or through which it will progress distance-relay characteristics can be placed in such a way that a desired kind of relay operation will be obtained only for a particular system characteristic.

SHORT CIRCUIT CALCULATIONS

For general studies, it is the practice to think of a power system in terms of a two-generator equivalent, as in Fig. 12. The generated voltages of the two generators are assumed to be equal and in phase. The equivalent impedance to the left of the relay location and to the right of the short

circuit are those that will limit the magnitudes of the short circuit currents to the actual known values. The short circuit is assumed to lie in the tripping direction of the relay.

The possible effect of mutual inductance from a circuit paralleling the portion of the system between the relay and the fault will be neglected. Also, load and charging current will be neglected; however, they may not be negligible if the fault current is very low.

Nomenclature to identify specific values or combinations of the quantities indicated on Fig. 12 will be as follows:

Z = system impedance viewed both ways from the fault

$$= \frac{Z_x \cdot Z_y}{Z_x + Z_y}$$

C = ratio of the relay current I to the total current in the fault

$$= \frac{Z_y}{Z_x + Z_y}$$

Subscripts a, b, c denote phase a, b, and c respectively. Positive phase sequence is assumed to be a, b, c. Subscripts 1, 2, and 0 denote positive, negative, and zero sequence respectively.

Three Phase Short Circuits. For a three phase fault, the positive sequence network is shown in Fig. 13 for quantities of phase a. Whenever the term "three phase" fault is used, it will be assumed that the fault is balanced; i.e., that only positive phase sequence quantities are involved. The quantity R_F is the resistance in the fault, assumed to be from line to neutral of each phase.

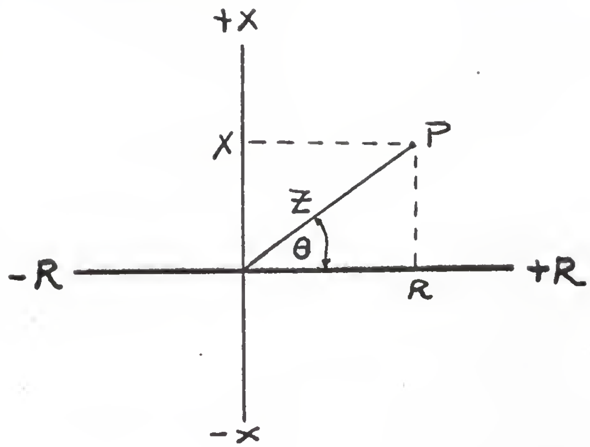

Figure 11. The R-X diagram.

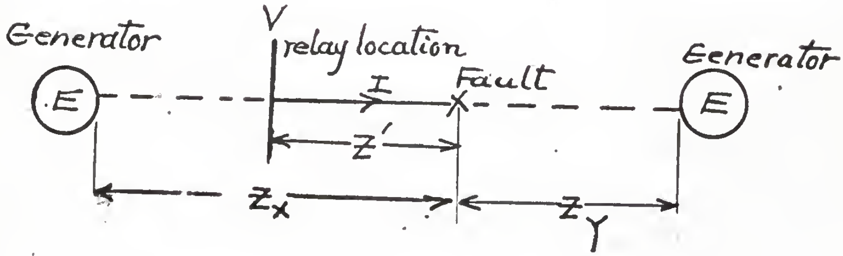

Figure 12. Equivalent-system diagram for defining quantities during fault.

By inspection, $$I_1 = \frac{E_1}{Z_1 \quad R_F}$$

$$I_{a_1} = \frac{Z_{Y_1} I_1}{Z_{Y_1} + Z_x} = C_1 I_1 = \frac{C_1 E_1}{Z_1 + R_F}$$

$$V_1 = I_1 R_F = \frac{E_1 R_F}{Z_1 + R_F}$$

$$V_{a_1} = V_1 + I_{a_1} Z_1' = \frac{E_1 R_F}{Z_1 + R_F} = \frac{C_1 F_1 Z_1'}{Z_1 + R_F}$$

Let $$\frac{E_1}{Z_1 + R_F} = \frac{1}{K}$$

Then $$K I_{a_1} = C_1$$

$$K V_{a_1} = R_F + C_1 Z_1'$$

Since there are no negative or zero sequence quantities for a three phase fault,

$$KI_{a_2} = 0$$

$$KI_{a_0} = 0$$

$$KV_{a_2} = 0$$

$$KV_{a_0} = 0$$

Therefore, the actual phase currents and line to neutral voltages at the relay location are:

$$KI_a = K I_{a_1} + KI_{a_2} + KI_{a_0} = C_1$$

$$KI_b = a^2KI_{a1} + aKI_{a2} + KI_{a0} = a^2C_1$$

$$KI_c = aKI_{a1} + a^2KI_{a2} + KI_{a0} = aC_1$$

$$KV_a = KV_{a1} + KV_{a2} + KV_{a0} = R_F + C_1Z_1'$$

$$KV_b = a^2KV_{a1} + aKV_{a2} + KV_{a0} = a^2(R_F + C_1Z_1')$$

$$KV_c = aKV_{a1} + a^2KV_{a2} + KV_{a0} = a(R_F + C_1Z_1')$$

If delta-connected current transformers are involved,

$$K(I_a - I_b) = (1-a^2)\,C_1$$

$$K(I_b - I_c) = (a^2-a)\,C_1$$

$$K(I_c - I_a) = (a-1)\,C_1$$

The line to line voltages are:

$$KV_{ab} = K(V_a - V_b) = (1-a^2)(R_F + C_1Z_1')$$

$$KV_{bc} = K(V_b - V_c) = (a^2-a)(R_F + C_1Z_1')$$

$$KV_{ca} = K(V_c - V_a) = (a-1)(R_F + C_1Z_1')$$

Line To Line Short Circuit. Fig. 14 shows the phase a phase-sequence net work for a phase b to phase c fault. By inspection,

$$I_1 = \frac{E_1}{Z_1 + Z_2 + R_F} = \frac{E_1}{2Z_1 + R_F}$$

Assuming $Z_2 = Z_1$

Let $\dfrac{E_1}{2Z_1 + R_F} = \dfrac{1}{K}$

R_F : Resistance between faulted phase

R_F : Line to line $\neq R_F$ (three phase)

$$V_1 = (I_1 - I_2)\frac{R_F}{2} - I_2 Z_2 = I_1 R_F + I_1 Z_1$$

Since $I_2 = -I_1$, $Z_2 = Z_1$

$$Va_1 = V_1 + I_{a_1} Z_1' = I_1 (R_F + Z_1 + C_1 Z_1')$$

$$= \frac{1}{K}(R_F + Z_1 + C_1 Z_1')$$

Since $Ia_1 = C_1 I_1$ By definition

$$KV_{a_1} = R_F + Z_1 + C_1 Z_1'$$

$$V_2 = -I_2 Z_2 = I_1 Z_1$$

$$V_{a_2} = V_2 + I_{a_2} Z_2'$$

But $Z_2' = Z_1'$ for transmission line

AND $I_{a_2} = C_2 I_2$ By definition

Hence $V_{a_2} = I_1 Z_1 + C_2 I_2 Z_1'$

Assume that $C_2 I_2 = -C_1 I_1$ and hence:

$$V_{a_2} = I_1 Z_1 - C_1 I_1 Z_1' = I_1 (Z_1 - C_1 Z_1')$$

$I_1 = \frac{1}{K}$, $KV_{a_2} = Z_1 - C_1 Z_1'$

By definition $I_{a_1} = C_1 I_1$

$$K I_{a_1} = C_1$$

Since $I_{a_2} = -I_{a_1}$, $K I_{a_2} = -K I_{a_1} = -C_1$

Since there are no zero sequence quantities.

$$K V_{a_0} = 0$$

$$K I_{a_0} = 0$$

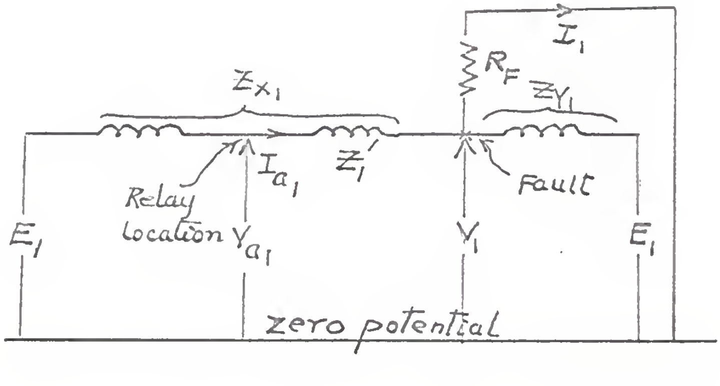

Figure 13. Positive-phase-sequence network for a three-phase fault.

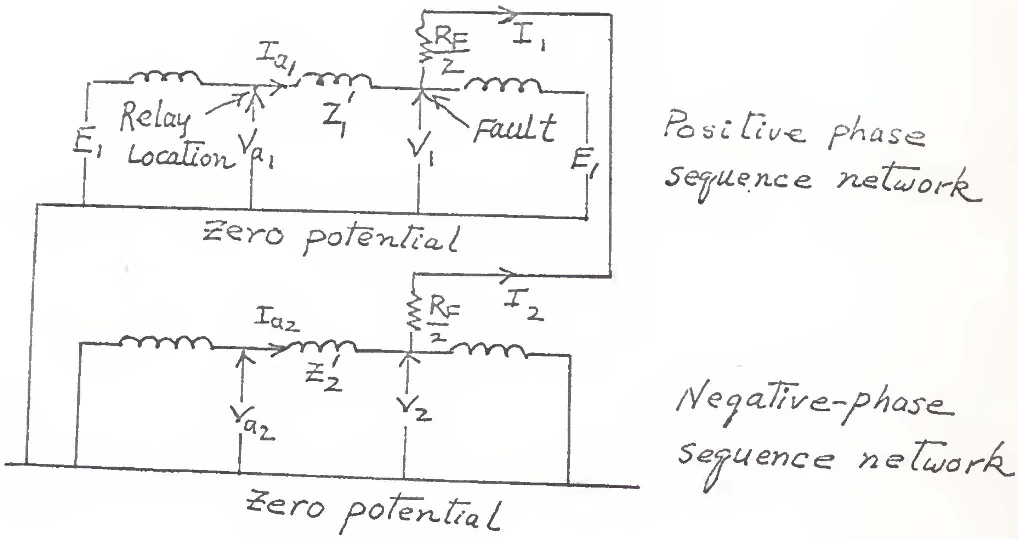

Figure 14. Phase a phase sequence networks for a phase-b-to phase c fault.

Table II Current Distribution at Fault

Quantity at Relay Location	Value of Quantity for Various Types of Fault		
	3ϕ	ϕ_b to ϕ_c	Phase a to Ground
KI_{a_1}	C_1	C_1	C_1
KI_{a_2}	0	$-C_1$	C_1
KI_{a_0}	0	0	C_0
KI_a	C_1	0	C_0+2C_1
KI_b	a^2C_1	$(a^2-a)C_1$	C_0-C_1
KI_c	aC_1	$-(a^2-a)C_1$	C_0-C_1
$K(I_a-I_b)$	$(1-a^2)C_1$	$-(a^2-a)C_1$	$3C_1$
$K(I_b-I_c)$	$(a^2-a)C_1$	$2(a^2-a)C_1$	0
$K(I_c-I_a)$	$(a-1)C_1$	$-(a^2-a)C_1$	$-3C_1$
$K(I_a+I_b+I_c)$	0	0	$3C_0$
K	$\dfrac{Z_1+R_F}{E_1}$	$\dfrac{2Z_1+R_F}{E_1}$	$\dfrac{2Z_1+Z_0+3R_F}{E_1}$

TABLE VIII Voltages During Faults

Quantity at Relay Location	Value of Quantity for Various Types of Fault: Three Phase	Phase b to Phase c	Phase a to Ground
KV_{a_1}	$c_1 z' + R_F$	$c_1 z_1' + z_1 + R_F$	$c_1 z' + z_1 + z_0 + 3R_F$
KV_{a_2}	0	$z_1 - c z_1'$	$c_1 z_1' - z_1$
KV_{a_0}	0	0	$c_0 z_0' - z_0$
KV_a	$c_1 z_1' + R_F$	$2 z_1 + R_F$	$2c_1 z_1' + c_0 z_0' + 3R_F$
KV_b	$a^2(c_1 z_1' + R_F)$	$(a^2-a)c_1 z_1' - z_1 + a^2 R_F$	$-c_1 z_1' + (a^2-a) z_1 + (a^2-1) z_0 + c_0 z_0' + 3a^2 R_F$
KV_c	$a(c_1 z_1' + R)$	$(a-a^2)c_1 z' - z_1 + a R_F$	$-c_1 z_1' + (a-a^2) z_1 + (a-1) z_0$ $c_0 z_0' + 3aR_F$
$K(V_a - V_b)$	$(1-a^2)(c_1 z_1' + R_F)$	$(a-a^2) c_1 z_1' + 3z_1 + (1-a^2) R_F$	$3c_1 z' - (a^2-a) z_1 - (a^2-1)(z_0 + 3R_F)$
$K(V_b - V_c)$	$(a^2-a)(c_1 z_1' + R_F)$	$2(a^2-a) c_1 z_1' + (a^2-a) R_F$	$2(a^2-a) z_1 + (a^2-a)(z_0 + 3R_F)$
$K(V_c - V_b)$	$(a-1)(c_1 z' + R_F)$	$(a-a^2) c_1 z_1' - 3z_1 + (a-1) R_F$	$-3c_1 z_1' + (a-a^2) z_1$ $(a-1)(z_0 + 3R_F)$
$K(V_a + V_b + V_c)$	0	0	$3(c_0 z_0' - z_0)$
K	$\dfrac{z_1 + R_F}{E_1}$	$\dfrac{2z_1 + R_F}{E_1}$	$\dfrac{2z_1 + z_0 + 3F}{E_1}$

Discussion of Assumptions. The error in assuming the positive and negative phase sequence impedances to be equal depends upon the operating speed of the relay involved and upon the location of the fault and relay relative to generator. All the error is in the assumed generator impedances. The negative sequence reactance will grow larger, from subtransient to synchronous, within a very short time after a fault occurs. Unless the fault is at the terminals of a generator, the constant impedance of transformer and lines between a generator and the fault will tend to lessen the effect of changes in the positive sequence reactance of the generator.

The assumption that positive and negative sequence impedances are equal is sufficiently accurate for analyzing the response of high speed relays to operate after a fault has occurred. The equivalent positive sequence reactance of a generator is nearly enough equal to the negative sequence reactance, that there is negligible over-all error in assuming them to be equal.

DETERMINATION OF DISTANCE RELAY OPERATION

Modern distance relays are single phase types. The three relays used for phase fault protection are supplied with the following combination of current and voltage, called "delta voltages" and "delta currents".

Current	Voltage
$I_a - I_b$	$V_{ab} = V_a - V_b$
$I_b - I_c$	$V_{bc} = V_b - V_c$
$I_c - I_a$	$V_{ca} = V_c - V_a$

TABLE IV Impedance "seen" by Phase Distance Relays For Various Kinds of Short Circuits

Ratio	Value of Ratio for Various Types of Fault: 3ϕ	$\phi_b - \phi_c$	ϕ_a - Ground
$\frac{K(V_a-V_b)}{K(I_a-I_b)}$	$Z_1' + \frac{R_F}{C_1}$	$Z_1' - j\sqrt{3}\, Z_{x_1} - \frac{a}{C_1} R_F$	$Z_1' + j\frac{\sqrt{3}}{3} Z_{x_1} + \frac{(1-a^2)(Z_0+3R_F)}{3C_1}$
$\frac{K(V_b-V_c)}{K(I_b-I_c)}$	$Z_1' + \frac{R_F}{C_1}$	$Z_1' + \frac{R_F}{2C_1}$	∞
$\frac{K(V_c-V_a)}{K(I_c-I_a)}$	$Z_1' + \frac{R_F}{C_1}$	$Z_1' + j\sqrt{3}\, Z_{x_1} - \frac{a^2}{C_1} R_F$	$Z_1' - j\frac{\sqrt{3}}{3} Z_{x_1} - \frac{(a-1)(Z_0+3R_F)}{3C_1}$

For a three phase fault, all three relays "see" the positive sequence impedance of the circuit between the relays and the fault, plus a multiple of the arc resistance. This multiple depends on the fraction of the total fault current that flows at the relay location and is larger for smaller fractions.

These values of impedance seen by the three relays for a phase b to phase c fault can be shown as Fig. 15. The terms Z_{bc}, Z_{ab}, and Z_{ca} identify the impedance seen by the relays obtaining voltage between phases bc, ab, ca, respectively.

For phase b to phase c fault with or without arcs, and located any where on a line section from the relay location out to a certain distance, the heads of the three impedance radius vectors will lie on or within the boundaries of the shaded areas of Fig. 16. These areas would be generated if we were to let Z_1' and R_F of Fig. 15 increase from zero to the value shown.

To use the data shown by Fig. 15, it is only necessary to superimpose the characteristic of any distance relay using one of the combinations of delta current and voltage in order to determine its operating tendencies. This has been done on Fig. 15 for an impedance type distance relay adjusted to operate for all faults having any impedance within the shaded area Z_{bc}. Had the three fault areas Z_{ab}, Z_{bc} and Z_{ca} been shown on three different R-X diagrams, the relay characteristic would still have looked the same on all three diagrams, since the practice is to adjust all three relays alike. For any portion of shaded area lying inside the relay characteristic, it is thereby indicated that for a certain location of the phase b-phase c fault, the relay represented by that area will operate.

For adjustment of Fig. 16, all three relays will operate for nearby faults, represented by certain values of Z_{ca} and Z_{ab} where the shaded areas fall within the operating characteristic of the impedance relay. Such operation is not objectionable, but the target indications might lead one to conclude that the fault was three phase instead of phase to phase.

We may generalize the picture of Fig. 15 and think of the Z_{bc} area as representing the appearance of a phase to phase fault to the distance relay that is supposed to operate for that fault. Then the Z_{ca} area shows the appearance of the fault to the relay using the voltage lagging the faulted phase voltage sometimes called the "lagging" relay, and Z_{ab} shows the

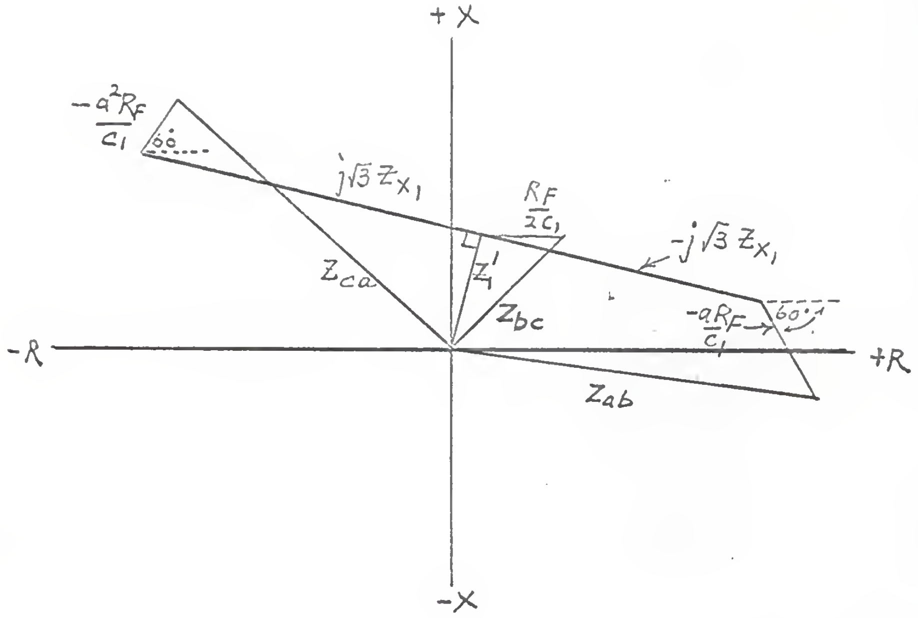

Figure 15. Impedance seen by each of the three phase distance relays for a phase b to phase c fault.

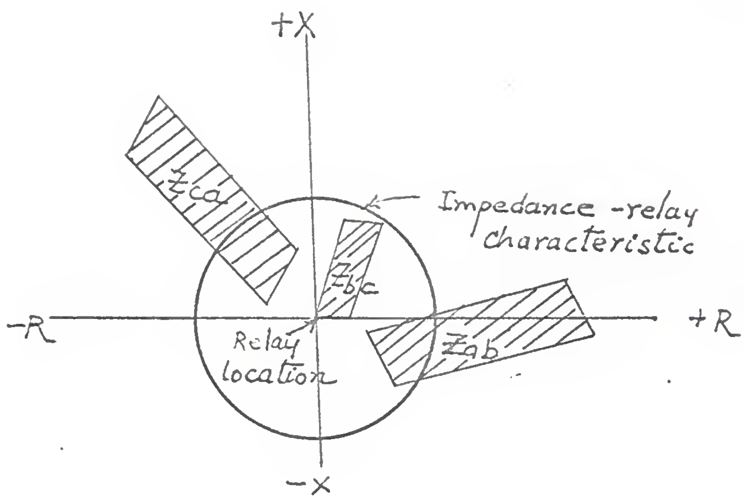

Figure 16. Impedance area seen by the 3 phase distance relay for various location of phase-b to phase-c fault with and without arc.

appearance of the fault to the relay using the voltage leading the fault phase voltage, sometimes called the "leading" relay.

Constructing the diagram of Fig. 15 graphically, as in Fig. 17 neglecting the effect of arc resistance. Draw the line OF equal to Z', of Fig. 15. Extend OF to A, making FA equal to Zx_1, the positive-phase sequence impedance from the fault to the end of the system back of relay location. Actually, FA is Z_{x_2}, but assuming the positive-phase-sequence impedances to be equal. Draw a line through F perpendicular to AF. From A, draw lines at 60° to AF until they intersect the perpendicular to AF at M and N. Then

$$OF = Zbc$$

$$OM = Zbc$$

$$ON = Zca$$

A phase a to ground fault appears to a phase distance relay as shown in Fig. 18 except for the last term in Table IV. This diagram can be constructed graphically by drawing the two construction lines at 30° to FA.

It is usually only necessary to locate the point representing the appearance of a fault to the one relay that should operate for the fault. In other words, only the position is located. The information gained from such constructions explains why relay target indications cannot always be relied on for determining what kind of fault occurred; in other words, three targets (apparently indicating a three-phase fault) might show for a nearby phase to phase fault. Also, a phase relay might show a target for a nearby single-phase to ground fault.

The construction has also been useful for explaining a tendency of

certain ground relays to 'over reach' for phase faults. Because of this tendency it is customary to provide means for block tripping by ground distance relays when a fault involves two or more phases, or at least to block tripping by ground relays that can over reach.

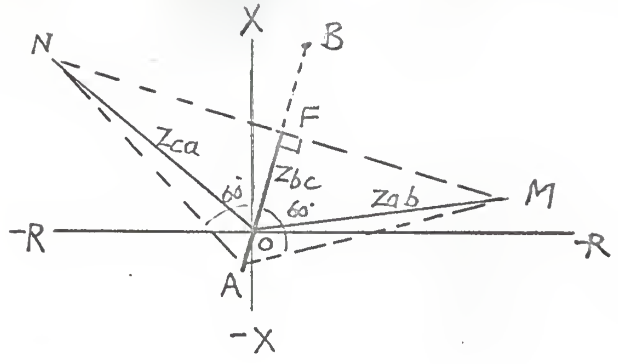

Figure 17. Graphical construction of Fig. 15, neglecting the effect of arc resistance.

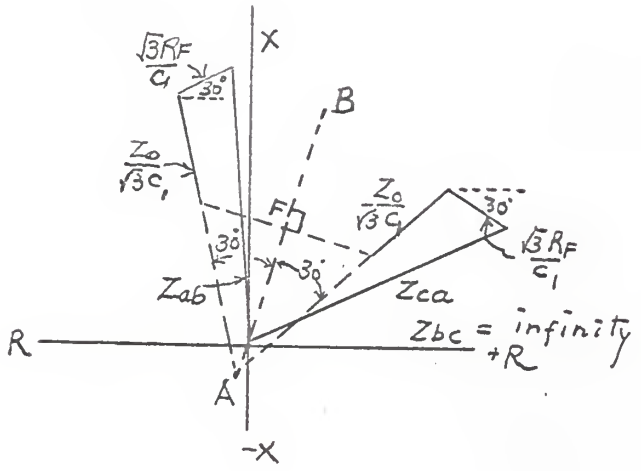

Figure 18. Appearance of a phase a to ground fault to phase distance relays.

POWER SWINGS AND LOSS OF SYNCHRONISM

When a fault occurs, only those relays which control the fault section should trip. During a fault, and also after a circuit is switched out of service, the synchronous machines of the system undergo changes in relative position of their rotors. With constant internal generated voltage, the phase angle between these voltages will vary until a new condition of equilibrium is established; or if the disturbance is sufficiently severe, loss of synchronism will result. In cases where there will be no loss of synchronism, it is important that those relays which do not control the faulty section do not trip during power swings while the fault is on the system and also after it has been cleared.

The effects of swings and out of step operation on relays may be studied by referring to Fig. 19.

E_A, E_B = voltages behind transient reactance assumed constant in magnitude but varying in phase during swings or out of step condition; E_A leads E_B by variable angle δ

$$\mathbb{I} = \frac{E_A \angle\delta - E_B}{\mathbb{Z}}$$

$$\mathbb{E} = (1-m)\, E_A \angle\delta + m\, E_B$$

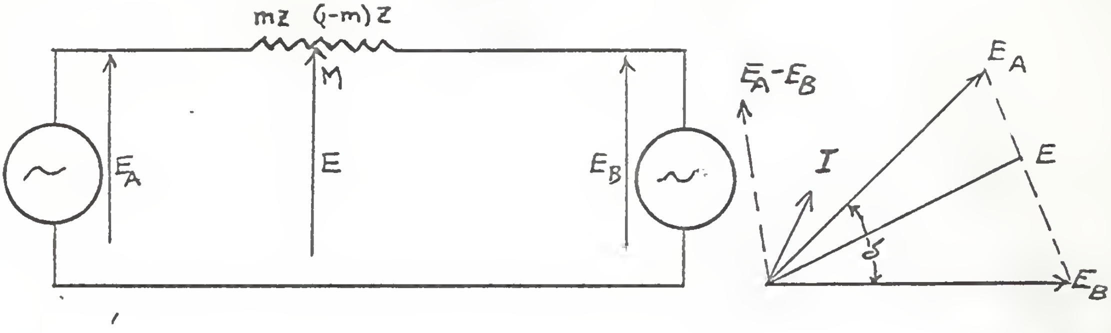

Figure 19. Two machine-system circuit and phasor diagram.

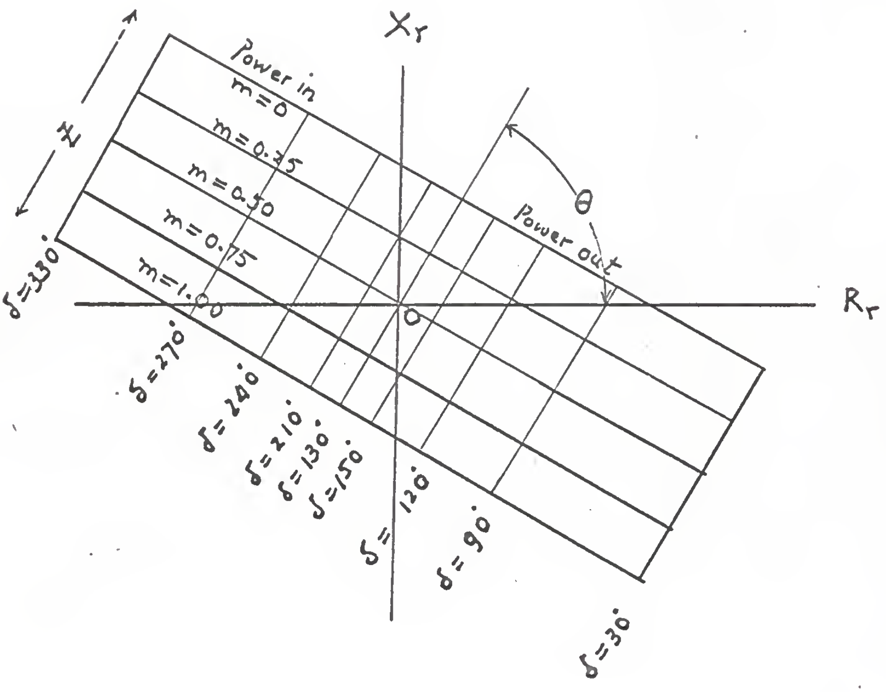

Figure 20. Loci of impedance $R_r + jX_r$ "seen" by distance relays during swinging or out of synchronism conditions or two machine system.

Effect on distance relays

The impedance "seen" by relays at M.

$$Z_r = \frac{E}{I} \qquad \frac{(1-m)E_A\angle\delta + mE_B}{E_A\angle\delta - E_B} \cdot Z$$

E_A, E_B and m are constant.

If $E_A = E_B$

$$\frac{Z_r}{Z} = \frac{(1-m)\angle\delta + m}{\angle\delta - 1} = \frac{-m(\angle\delta - 1) + \angle\delta}{\angle\delta - 1}$$

$$= -m + \frac{1}{1-\angle -\delta} = -m + \frac{1+\angle\delta}{(1-\angle -\delta)(1+\angle\delta)}$$

$$= -m + \frac{1+\angle\delta}{1+\angle\delta - \angle -\delta - 1} = -m\frac{1+\cos\delta + j\sin\delta}{2j\sin\delta}$$

$$= \left(\tfrac{1}{2}-m\right) - j\left(\frac{1+\cos\delta}{2\sin\delta}\right) = \left(\tfrac{1}{2}-m\right) - j\tfrac{1}{2}\cot\tfrac{\delta}{2}$$

At $\theta = 0$ the apparent impedance is infinite.

At $\theta = 180$ the voltage becomes zero at the middle of the line, and therefore appears to be a three phase short circuit at $m = 0.5$.

If $E_A \neq E_B$, the loci are circles with their centers on extensions of the total impedance line and the impedance never becomes infinite. An example of the loci of impedance "seen" by relays for different E_A/E_B are shown in Fig. 21 and 22.

In Fig. 22 for most practical purposes it is accurate enough to use the straight line for all values of E_A/E_B.

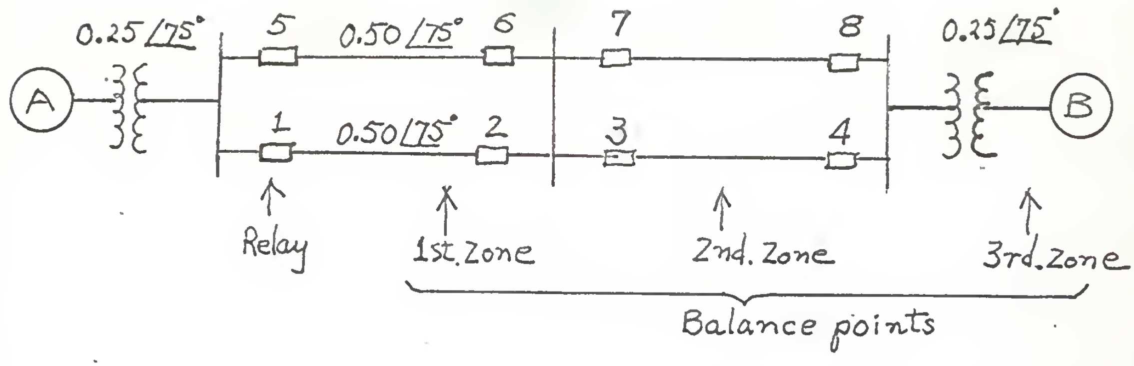

Figure 21. Two-machine system used for analysis of relay operation during out of synchronism with $\frac{E_A}{E_B}$ = 1.15, 1.00, 0.87.

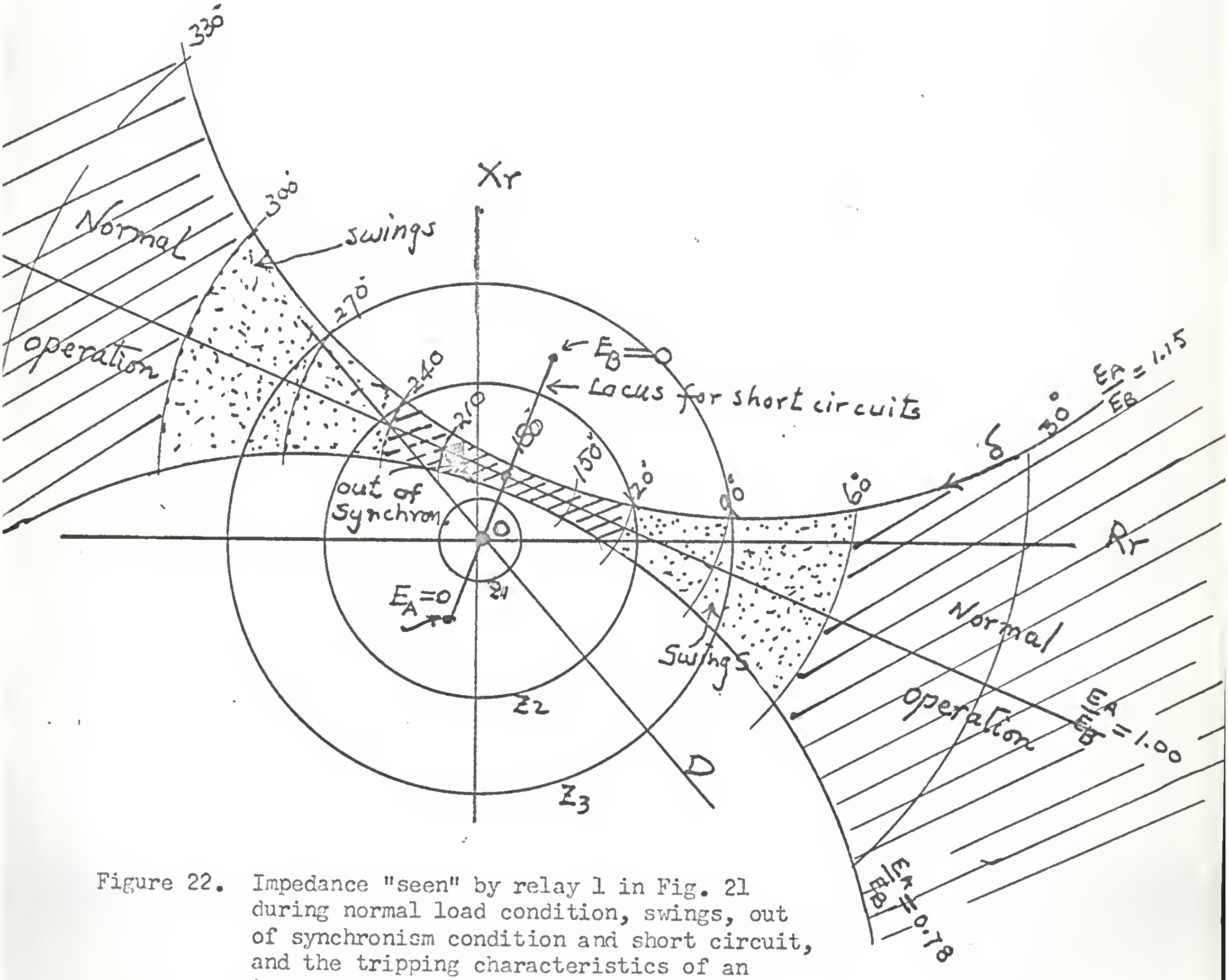

Figure 22. Impedance "seen" by relay 1 in Fig. 21 during normal load condition, swings, out of synchronism condition and short circuit, and the tripping characteristics of an impedance relay.

Effect on over current relays.

The current locus of the two machine system in Fig. 19 is given by $I = \frac{E_A \angle\delta - E_B}{Z}$ and is shown in Fig. 23. It is a circle with center at the end of the phasor $-E_B/Z = (E_B/Z) \angle 180-\theta$ and radius E_A/Z .

The reference phasor in Fig. 24 is the voltage at m 0.25, E_A 1.15 E_B 1.00 and Z 1.00 $\angle 75^\circ$. The tripping characteristic of the over-current relay shows the current element set to pick up at 1.5 per unit current and a directional element with maximum torque at 45 degrees lag.

Effect on carrier pilot relays. The tripping characteristics of distance type carrier-pilot relays are similar to those of directional distance relays set to reach beyond the end of the protected line, except that tripping occurs only when tripping indications are given simultaneously at both ends of the line as shown in Fig. 25.

Some carrier pilot systems are first zone impedance elements which trip independently of a carrier and second zone impedance elements which trip under carrier supervision. The tripping characteristics are shown in Fig. 26

The diagonally shaded area of Fig. 26 bounded by D and Z_1 and D' Z_1' represents non-carrier tripping at ends M and N respectively. The vertically shaded area bounded by D, Z_2, D' and Z_2' represents carrier tripping. In some of the unshaded area there may be time delay tripping independent of carrier, which would trip the lines on swings or on loss of synchronism if the operating point should remain inside the trip area long enough.

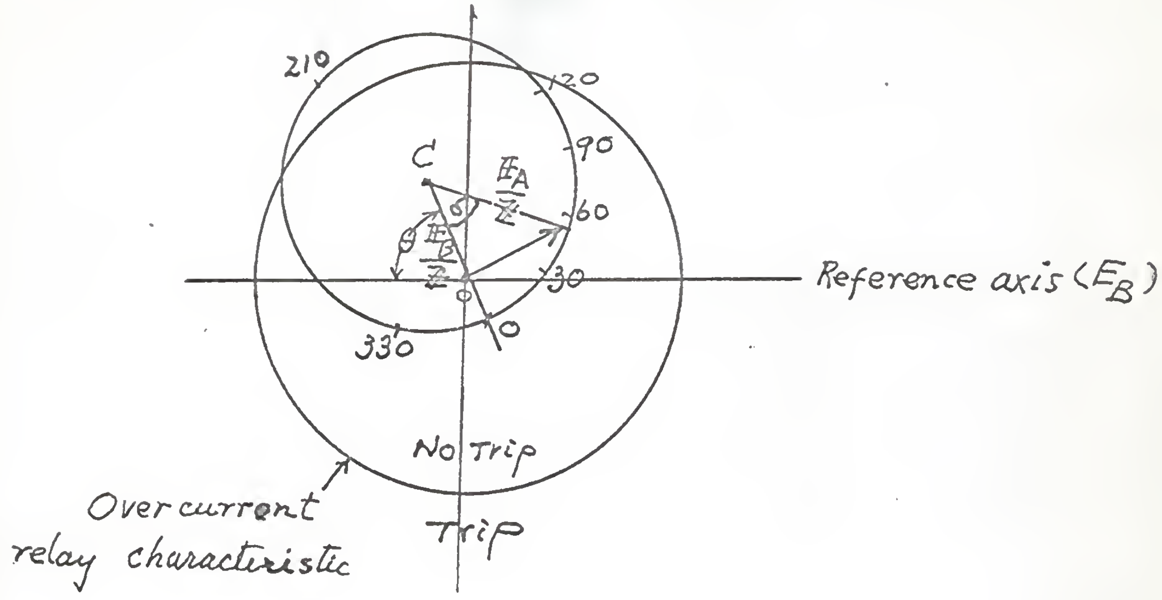

Figure 23. Locus of phasor current of the two machine system of Fig. 19 during swinging or out of synchronism conditions, and tripping characteristic of an over current relay.

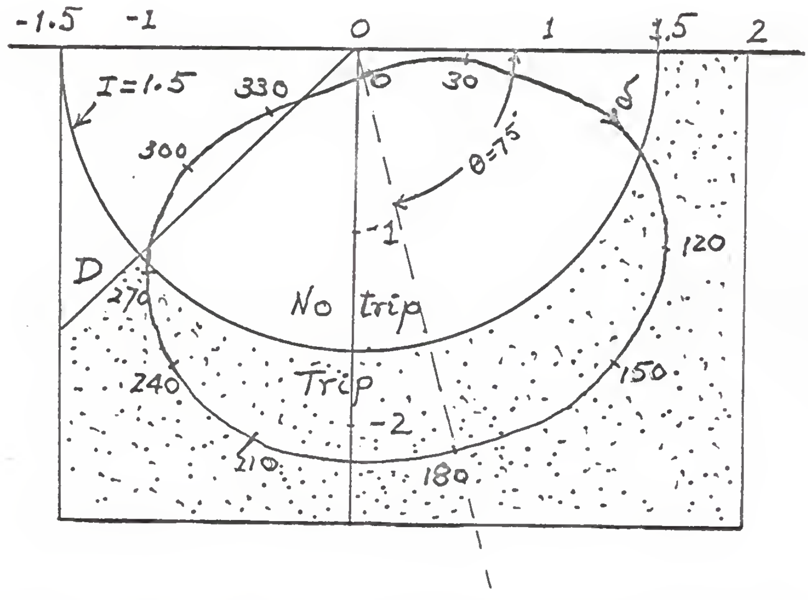

Figure 24. Locus of phasor current of the two machine system of Fig. 19 during swinging or out of synchronism conditions and tripping characteristic of a directional over current relay at $m=0.25$.

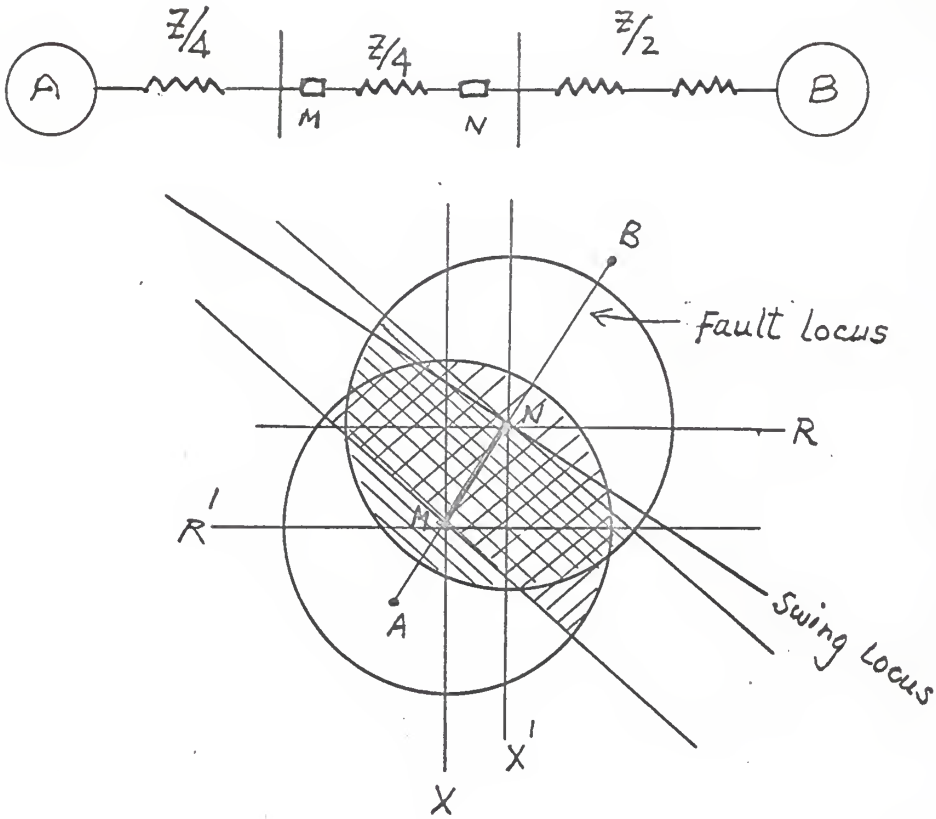

Figure 25. Superposition of the tripping characteristics of impedance relays at opposite ends of a transmission line MN to give the tripping characteristic of a carrier-pilot relay system. The tripping area is double-cross-hatched.

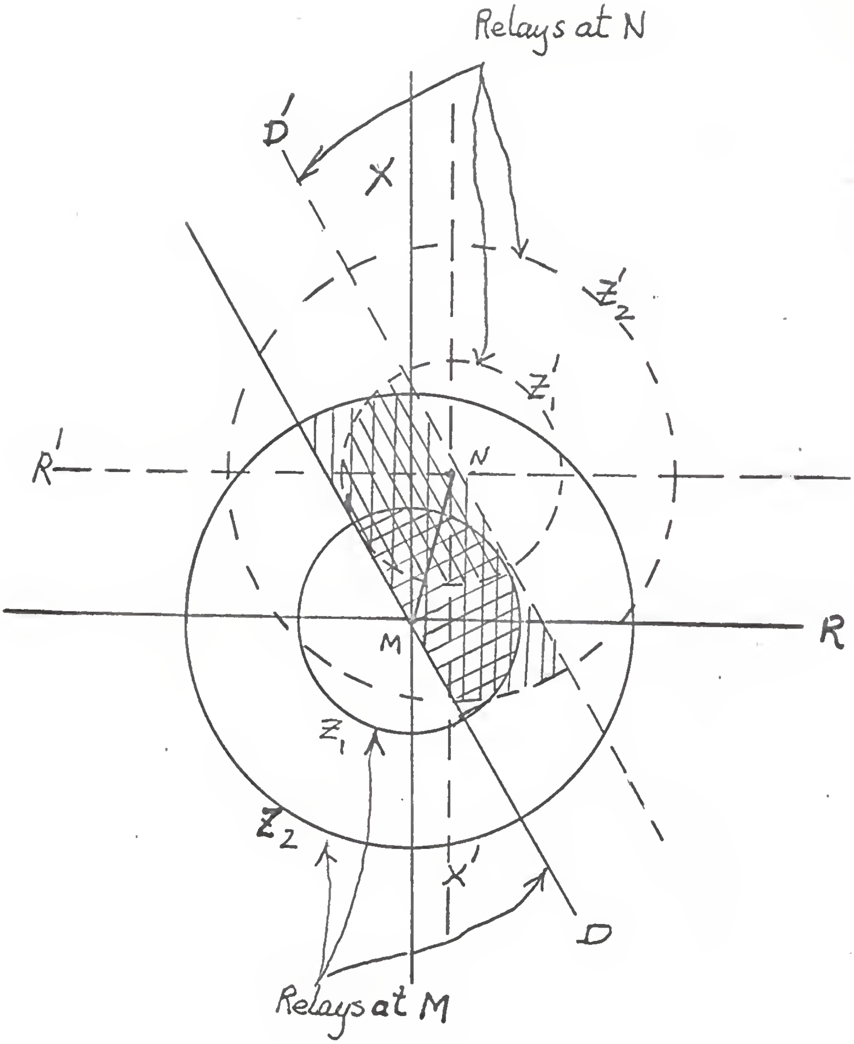

Figure 26. Carrier and non-carrier tripping characteristics of carrier-pilot impedance relays.

PREVENTION OF TRIPPING DURING SWINGS

It is desired to prevent tripping during swings in some cases from which the power system will recover and yet to allow tripping during out of step operation. It is necessary to restrict the tripping area of the relay characteristic to a range of angles on the swing impedance locus which is reached only during out-of-step conditions. The relays should be so designed that their tripping areas do not include any part of the swing impedance locus that lies in the stable range. The tripping area must be wide enough to include fault resistance.

The angular range covered by the mho relay is too wide, it may be narrowed to any desired extent by the use of additional relay elements as shown in Fig. 27.

In Fig. 27 the impedance seen during metallic faults on the protected section lies on the line O N, arcing faults lie to the right of O N. The tripping area, which is marked with dots, includes and surrounds the fault area and is bounded by mho unit M, O_1, O_2. The ohm units are similar to reactance units except that they respond to impedance at angles at 160 degrees and - 30 degrees instead of $\neq$ 90 degrees. These angles are selected to make the characteristics of the ohm units parallel to the boundaries of the fault area, and the ohm settings are chosen to place the characteristics close, but not too close, to those boundaries.

Because the contacts of three units are connected in series, tripping can occur only for an impedance in the trip area. The settings of the ohm units control the angular range of tripping on swings. The setting of the mho unit controls the reach of the relay for faults.

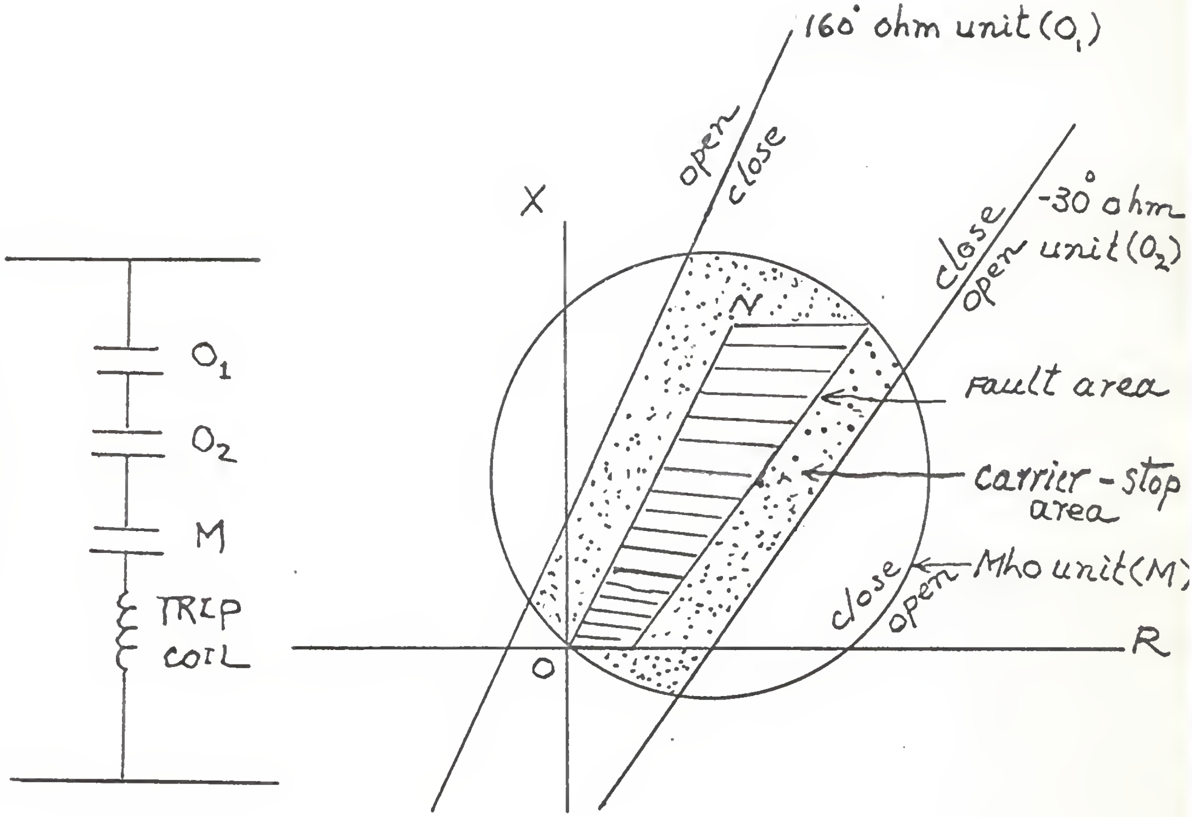

Figure 27. The use of ohm relay units as "blinders" to narrow the angular range in which tripping can occur during fault.

OUT OF SYNCHRONISM TRIPPING WITH DISTANCE RELAYS

When a system goes out of synchronism distance relays interpret the condition as a traveling three phase fault. The three distance elements will trip in sequence as the disturbance comes within their setting, and will reset in the opposite sequence as the disturbance becomes remote. For three phase faults within the zone of the first element, all three distance elements will operate simultaneously. Discrimination between an out of step and a three phase fault is the time difference in the operation of impedance elements.

Tripping or block tripping is operated by auxiliary elements which are controlled by impedance elements.

Fig. 28 shows the circuit tripping on an out of synchronism condition. Under an out of step condition, Z_3 will operate first, followed after a time delay by Z_2, Z_1. In case of a fault, one, two or three impedance elements may be operated. In Fig. 28, the relay X is normally energized from the station battery and is of the slow to release type. It requires approximately four cycles to drop out.

Upon the occurrence of an out of step condition, Z_3 will operate, short circuit the operating coil of relay X, causing it to drop out if in the meantime Z_2 does not also operate. If Z_2 operates after this auxiliary relay X has dropped out, auxiliary relay Y will be energized and the trip circuit will be completed if Z_1 now operates. Under any other conditions the trip circuit cannot be completed. Thus, any sequence of impedance element operations which could be expected under fault conditions would not allow the sequence of operation to be completed and tripping would not occur.

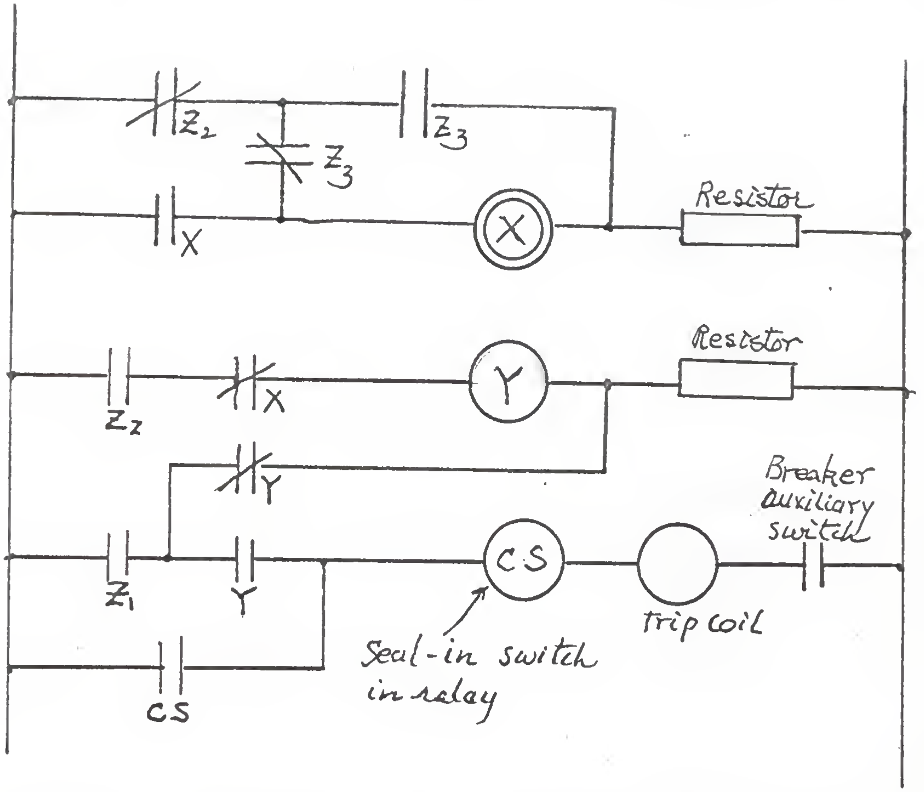

Figure 28. Connections of relay, used for obtaining tripping on out of synchronism. Three high speed impedance elements with grade impedance settings plus two auxiliary relays.

When conditions are returned to normal on the system, all impedance elements reset, and relay X is energized through the back contacts Z_2 and Z_3. The energizing of relay X and the resetting of Z_2 will be energize relay Y and thus restore both auxiliary relays to normal.

If a fault occurs within the impedance zone setting of the out of step relay, then after the fault is cleared, if the systems pull out of step because of the disturbance caused by the fault, the out of step relay will still operate properly. Under the fault condition, the relay impedance elements will take up a definite condition, the relay impedance elements will take up a definite position corresponding to whichever zone of the out of step relay the fault lies. After the fault is cleared, and the systems subsequently pull out of step, the out of step relay may or may not trip on the first swing as this would depend upon which zone was indicated by the original fault. However, at the conclusion of the first swing, all three impedance elements will be reset. On the second swing, as the system pulls out, these impedance elements will close in order and the system will trip on the second swing, assuming that the apparent short circuit of the out of step condition will fall within the zone covered by the out of step relay impedance setting.

OUT OF SYNCHRONISM BLOCKING

Out of synchronism blocking is nearly always used in conjunction with high speed distance relays, and often with carrier current relays. The impedance seen by the relays cannot change from a normal load value to a value in the trip area without passing across the buffer area as shown in Fig. 29. In event of a fault, the transition is made instantly; in event of out of synchronism operation, more slowly. The elapsed time between the crossing of the inner and the outer boundary of the buffer area serves to determine whether tripping shall be blocked.

In Fig. 29a and 29b, Z_2 is the circular characteristic of an impedance element, D, the straight line characteristic of a directional element, and Z_3 the characteristic of a higher impedance than element Z_2. In carrier pilot relays the buffer area may be identical with the area of carrier transmission, in which carrier is started by the third zone impedance element and is stopped by the combined action of the second zone impedance element and the directional element. X is an auxiliary relay having a pick-up time of 3 - 4 cycles. If contacts D_1, Z_2 and Z_3 close almost simultaneously, as they do when a fault occurs, the trip coil is energized before relay X has time to open the trip circuit. If Z_3 closed 4 or more cycles before both D and Z_2 have closed, as would occur in swinging or out of synchronism operation, relay X opens the trip circuit in time to prevent tripping, and holds it open until the swing impedance passes outside the Z_3 circle.

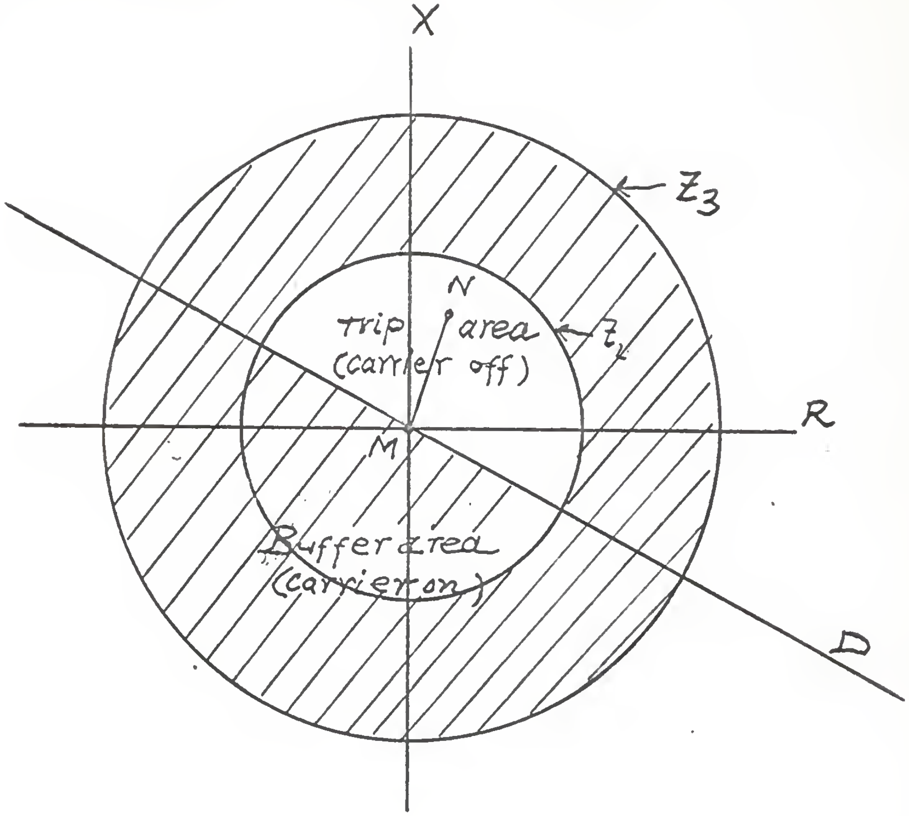

Figure 29a. Trip and buffer areas of impedance relay with out-of-synchronism blocking.

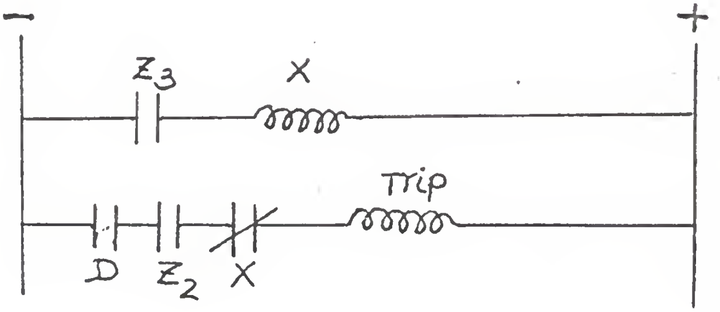

Figure 29b. Contact circuits of impedance relay with out-of-synchronism blocking.

PROTECTION OF MULTI-TERMINAL LINES

The principles of relay protection on multi-terminal lines are the same as for two-terminal lines. The conditions under which the relays are called upon to operate are a more difficult problem of relay application which becomes increasingly complicated as the number of terminals increases.

The impedances from one terminal to the other two may differ, introducing a problem in setting of distance type relays. Also, the impedance measurement at one terminal for a fault near the second terminal is affected by the current entering the line through the third terminal. The most satisfactory method of protecting a multi-terminal line is by the use of either a pilot wire or a carrier pilot protection scheme. The type of pilot wire relaying for these applications is the two wire a - c pilot wire type. For carrier applications, there are two types of systems, the directional comparison type, and the current or phase comparison type. Both of these carrier systems are the blocking type and depend on power flowing into the section from all terminals on an internal fault to permit tripping.

SELECTION OF RELAYING IN A HYPOTHETICAL SYSTEM

In Fig. 30, the two 70 mile transmission lines under discussion are required to serve primarily as the major power supply to load areas at stations H and J. The generating capability of the local station D is assumed to be limited by lack of cooling water, and the generating cost differential between A and D justifies substantial transmission of power to the load area near D from A in spite of rather heavy transmission line losses.

Relaying requirements. Phase to ground faults on the two lines are not too severe. The 138 kv transformer bank neutrals are solidly grounded at each terminal station of the line, thus providing adequate zero sequence currents under practically any system operating condition.

Phase-relaying requirements must receive more careful consideration, realizing that some compromises must be tolerated to meet the conflicting system operating requirements. The conditions which are to be met are as follows: (1) Positive and complete fault protection for all generating and system operating conditions. (2) Adequate allowance for conditions present by fault-arc impedance. (3) Some measure of back-up protection, should the proper circuit breaker fail to operate on fault. (4) Characteristics suitable for high-speed simultaneous tripping and reclosing. (5) Operating reliability with approximately double normal load plus the addition of current caused by system oscillations.

Certain combinations of circumstances may cause actual out of step conditions to exist between systems across one or both of the 70 mile lines. To prevent serious disruption of the power system, the two systems must be separated on the first complete swing.

Assumptions were made (Actual information could be obtained by use of an

A-C network analyzer) in order to provide information on phase relaying for the system, based on the phase faults with 1 circle relaying and 5 cycle circuit braker tripping. Three phase faults only were studied for simplicity. These are only slightly more severe to the over all system than those involving two phase and ground, which are more common.

Fig. 31 shows the impedance presented to the phase relay at station A on the line to station H for a fault at station A on the line to station J, this fault being cleared at both ends in 6 cycles, reclosed in 20 cycles, and retripped in 6 cycles. Swing curves taken for the system under this condition indicate that system itself is stable.

The characteristics of impedance, reactance, and modified impedance distance relay are illustrated with conventional settings of zone 1 and zone 2 tripping (zone 3 not shown). The reactance units require voltage restraint directional starting units, and the impedance elements require directional units.

Fig. 32 shows the impedance presented to the phase relays at A with a fault on the double circuit line at station A. This diagram indicates that successf l reclosure of both lines will prevent system instability; however, if only one line recloses successfully and the other recloses on a fault, the system will become unstable and will separate on the line which reclosed successfully. Successful reclosing of the lines following a transient fault requires that the phase relays should not trip on the resulting swing currents. For comparison, zone 1 and zone 2 settings of another form of modified impedance relay (with directional unit) are shown, indicating that the swing current is within the zone 2 setting for at least one-half second.

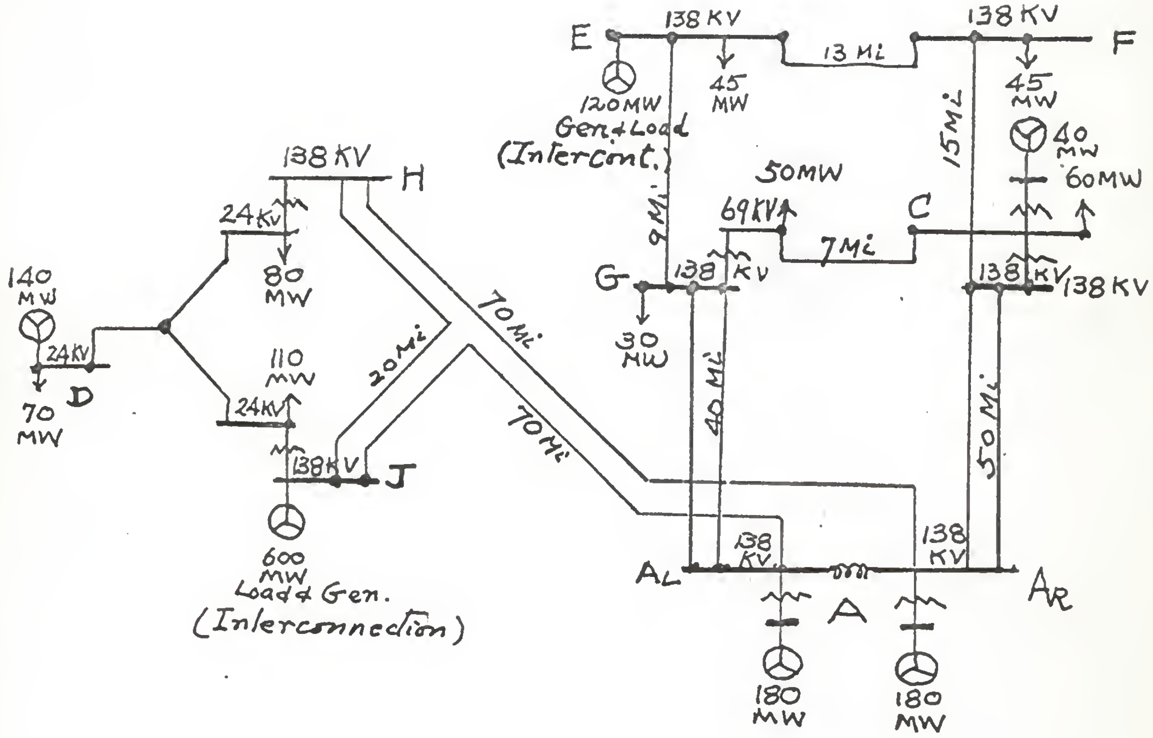

Figure 30. The two 70-mile 138 kv lines connecting station A, base load generating plant, with a net load interconnected area, substations H and J.

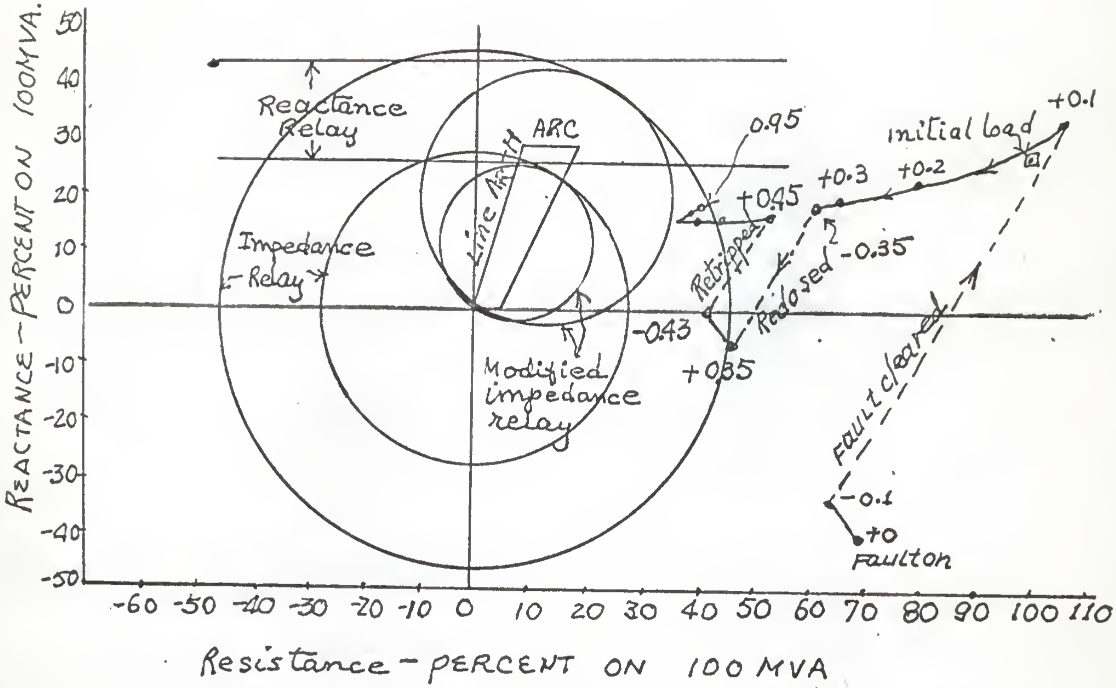

Figure 31. Impedance presented to relay at A_R circuit H with three phase fault at A_L circuit J.

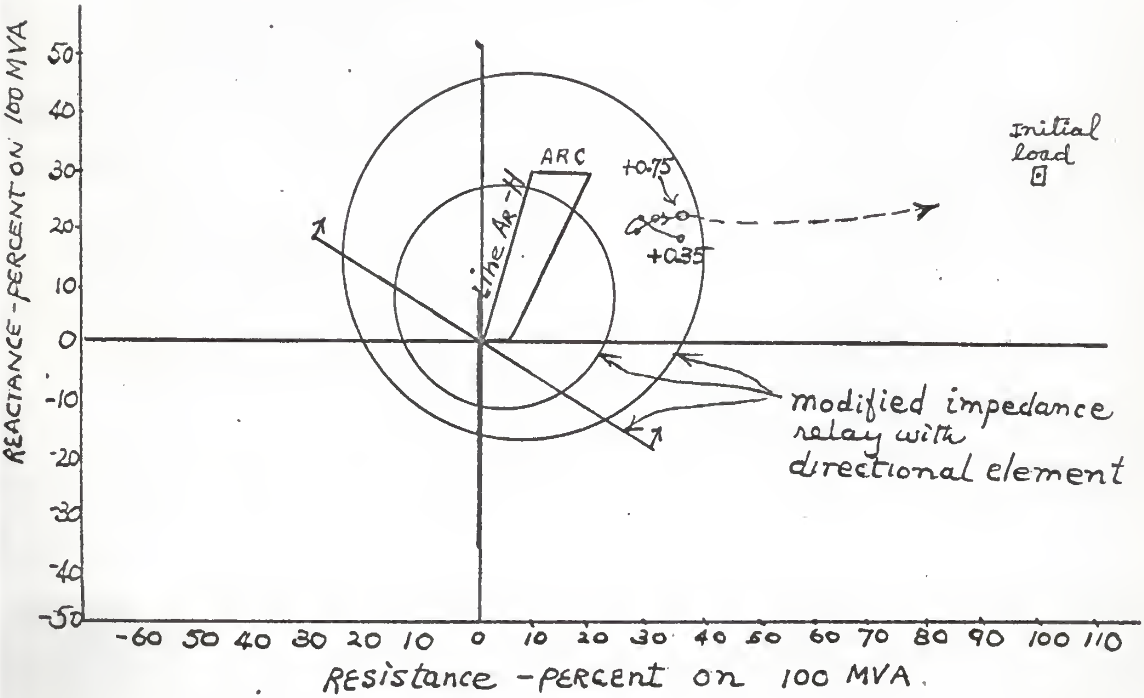

Figure 32. Impedance presented to relay at A_R circuit H following successful reclosing of line A_R - H and A_L - J.

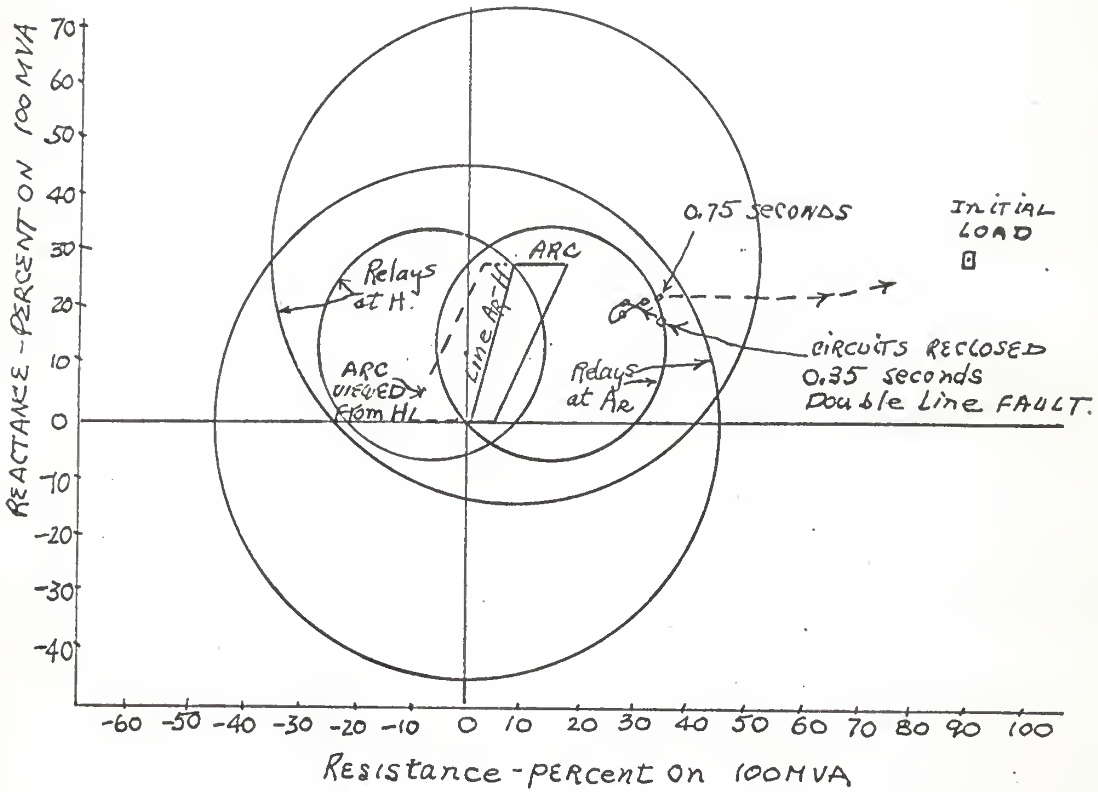

Figure 33. Carrier relay protection for circuit A_R - H.

Possible solutions. Two possible solutions may be considered for the 70 mile lines under consideration. One of these might be a carrier pilot scheme using a modified impedance or mho element, shown in Fig. 33. In this scheme, a long time back-up distance element (omitted for simplification) is in operation at all times, but zone 1 distance tripping (not shown) is normally cut out of service by the carrier control switch. The displaced circles operate to stop carrier, set up the tripping circuit, and also to control zone 2 timing, and the larger impedance circles start carrier.

However, the presence of a carrier signal cuts out zone 2 tripping. Thus, for normal operation, all line faults are cleared by carrier relays but it is necessary for the swing current impedance to enter the zone of both circles (near and far terminals) to cause tripping where the back-up element is set for a long enough time to avoid tripping on swings.

The use of the phase comparison type of carrier relaying may be advantageous for lines already equipped with distance relays, since this type of carrier protection is immune to swing current. Under this scheme, it would become necessary to provide for tripping on actual cut of step conditions using a modified setting of the distance relay elements. The reach of the zone 1 elements of the distance relays may be shortened so as to just overlap, thus ensuring that at least one end of the line will trip on actual out of step conditions, but minimizing the possibility of undesired tripping. It would become necessary to make zone 2 tripping nonautomatic for normal operation and to set zone 3 timing long enough to prevent tripping on systems swings.

Application of the phase comparison type of relaying would have to be closely studied to determine the sequence quantities which would be employed for fault detection. Due to the heavy load currents, both normal and abnormal,

which flow on the two lines involved, the relays applied must be able to discriminate correctly between normal and fault conditions. If such relays are completely de-sensitized for load current, faults beginning as three phase faults would not be correctly cleared. Both schemes have serious limitations and represent severe compromises with back up protection, especially the protection against the rare failure of a circuit breaker to trip.

CONCLUSION

This paper has briefly discussed the operation and characteristics for various types of protective relays, and the methods of discrimination when locating faults or other abnormal operating conditions in electrical systems: current value, time, distance, direction, balance current, comparison of direction of current flow, current differential.

A general study of the existing conditions on the system during faults and the methods of obtaining information by Symmetrical components simplified the process. Methods of selecting the correct type of relays, with selective settings to be made, to protect all parts of the system were studied. Analysis of the effect of normal conditions, short circuits, swings of large amplitude, and out of step operation upon relays and how they may be called upon to take the desired action in each of those circumstances was made.

Certain points which may determine the selection of relaying and reclosing applied to a system also has been discussed, and it is realized that each power system will require individual study for the selection of the appropriate protective schemes.

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APPLICATION OF PROTECTIVE RELAYS IN A POWER SYSTEM

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The function of protective relays in operation of a power system is to prevent or limit the damage during fault or any abnormal operation which occurs and to minimize their effect on the remainder of the system. Another function is to provide indication of the location and type of failure.

The relays operate from currents and voltages derived from current and potential transformers which for every type and location of failure, there is some distinctive difference in magnitude, frequency, phase angle, duration, rate of change, direction or order of change in voltage or current, and there are various types of protective relaying equipment available, each of which is designed to recognize a particular difference and to operate in response to it. Relays designed to operate in response to:

1. Magnitude difference generally are over current, differential, current comparison pilot or impedance relays.
2. Phase or direction difference generally are directional, phase comparison pilot or Mho type distance relays.
3. Duration or rate of change difference generally are impedance with time delay setting relays.

Relays may be classified according to two fundamentally different operating principles: Electromagnetic attraction, which operates on the principle of an armature being attracted to the poles of an electromagnet, and electromagnetic induction which uses the principle of the induction motor, where torque is developed by inducing a current in the rotor.

A general study of the existing conditions on the system during faults and the method of obtaining the three phase short circuit and line to line short circuit currents by symmetrical components to simplify the calculation process, and the impedance area seen by distance relays for various locations of faults were studied on an R - X diagram. Assumption of values of positive and negative sequence impedances in the system were discussed.

The effect of normal, short circuit, swings of large amplitude and out of synchronism operation upon distance relays, over current relays, carrier pilot relays on a two machine system, and how the relays respond and operate in the desired manner were studied.

In some cases it is desired to prevent tripping during swings from which the power system will recover, but to allow tripping as soon as the system goes out of synchronism. Also it is often desirable to prevent tripping even out of synchronism condition, because the point of separation should be properly chosen. Methods of preventing tripping were also studied.

Discussion of difficulty of relay application on multi-terminal lines due to problems in setting of distance type relays, and the use of either a pilot wire or a carrier pilot protected scheme are presented. The method of selecting relaying in a hypothetical system, where each system required individual study for appropriate protection, is discussed and a possible solution is presented.